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Propagation of Electromagnetic Beams in a HANE Environment: A Preliminary Study of Refraction Effects

J. D. HUBA

Geophysical and Plasma Dynamics Branch
Plasma Physics Division

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We present results for the deflection of 1μ, 10μ, and 1 cm radiation propagating through an ionospheric nuclear environment. We first derive a relatively simple expression for the deflection of an electromagnetic beam as it passes through a number of nuclear striations. We then develop a nuclear striation model which assumes that the striations are aligned with the earth's magnetic field, and uses a distribution of transverse scale sizes based upon observational data from the Checkmate event. ~~We find that~~ the 1 μ and 10 μ radiation is relatively unaffected by the nuclear environment, i.e., the deflection of the beam should not adversely impact SDI systems. On the other hand, 1 cm radiation is strongly refracted by the nuclear striations and SDI systems based upon microwaves are likely to be severly degraded in a nuclear environment. A suggested mitigation technique is to propagate the radiation perpendicular to the geomagnetic field.

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CONTENTS

PROPAGATION OF ELECTROMAGNETIC BEAMS IN A HANE ENVIRONMENT: A PRELIMINARY STUDY OF REFRACTION EFFECTS

I. INTRODUCTION

An important aspect in the design of an SDI architecture is understanding the operation of potential SDI systems in a severely disturbed atmospheric environment; in particular, that produced by high altitude nuclear explosions (HANEs). In order for SDI to be an effective deterrent, it is clear that its systems will have to be operational in a HANE environment. The propagation of electromagnetic waves (or beams) is crucial to the success of a number of systems. For example, microwave propagation ($f \sim 20 - 40$ gHz with $\lambda \sim$ few cm) is a key aspect to proposed communication systems, and laser propagation ($f \sim 30 - 300$ tHz with $\lambda \sim$ few microns) is being considered for communications, detection, and guidance systems.

The most striking feature of the HANE environment which can degrade electromagnetic wave propagation is the generation of high density, field-aligned striations. It is well known that when HANEs deposit their energy (e.g., x-ray, uv, debris, etc.), they produce an enormous amount of additional ionization in the ionosphere. Consider the fact that a single 1MT device exploded at 200 km produces as much plasma as normally exists in the global ambient ionosphere. This enhanced ionization survives for many hours after the burst. For a single burst, the electron density can reach values as high as $n_e \sim 10^9$ cm^{-3}; this is 3 orders of magnitude greater than the highest ambient electron density ($n_e \sim 10^6$ cm^{-3}). Preliminary calculations indicate that in a highly stressed multi-burst environment, the electron density can reach values as high as $n_e \sim 10^{11}$ - 10^{12} cm^{-3}. In addition to intense ionization levels, it is also known

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that the nuclear ionization is not uniform; geomagnetic field-aligned striations form within minutes after the burst. These striae have been observed in all of the high altitude nuclear detonations associated with the Fishbowl test series.

An obvious problem that needs to be addressed regarding the propagation of electromagnetic waves (or beams) in the nuclear environment is refraction of the beam. That is, as the beam enters and exits field-aligned striations, it will be deflected because of the change in the index of refraction. The purpose of this paper is to study this problem; specifically, to answer the question: how much will an electromagnetic beam be deflected as it passes through a striated nuclear ionosphere? As a preliminary study we consider an idealized physical model for a 'worst case' situation. The philosophy is the following. If a relatively simple and physically reasonable analysis indicates that there will not be a targeting problem because of refraction under these circumstances, then there is no need to perform further detailed studies; if there is a problem associated with refraction, then additional, more detailed studies would be warranted to determine the effect of refraction more accurately. We emphasize that we are only considering refractive effects. There are several other issues which must be investigated to fully understand the impact of a nuclear environment on electromagnetic wave propagation (e.g., beam quality and coherence, modulation, focussing, etc.).

The organization of the paper is as follows. In the next section we develop the refraction model and nuclear striation model to be used in the analysis. In Section III we present our results for a variety of electromagnetic waves and nuclear environments. Finally, we present our conclusions in the last section.

II. MODEL

The geometry and physics of our refraction model are illustrated in Fig. 1. We assume that an electromagnetic wave is propagating from left to right. It starts in the ambient plasma (characterized by a density n_1 and an index of refraction N_1), propagates into a nuclear striation (characterized by a density n_2 and an index of refraction N_2), and then back into the ambient plasma. We are interested in calculating Δy which is a measure of the deflection of the wave. The derivation of Δy is given as follows.

From the geometry shown in Fig. 1 we see that

$$\Delta y = D \sin \Delta\theta \tag{1}$$

where $\Delta\theta = \theta_2 - \theta_1$. We also note that

$$D = 2R/\cos \theta_2 \tag{2}$$

where R is the radius of the plasma striation. Thus, we can rewrite (1) as

$$\Delta y = 2R\,(\cos \theta_1 \tan \theta_2 - \sin \theta_1) \tag{3}$$

where we have used simple trignometric identities. Assuming that θ_1 and R are input parameters, we now have to determine θ_2.

We find θ_2 based upon Snell's law, namely,

$$N_1 \sin \theta_1 = N_2 \sin \theta_2 \tag{4}$$

where N_1 and N_2 are the indices of refraction and are given by

$$N_{1,2} = (1 - \omega^2_{pe1,2}/\omega^2)^{1/2}. \quad (5)$$

Here, $\omega^2_{pe1,2} = 4\pi n_{1,2}e^2/m_e$ is the square of the plasma frequency. From (4) it is straightforward to obtain

$$\tan\theta_2 = \frac{N_1 \sin\theta_1}{(N_2^2 - N_1^2\sin^2\theta_1)^{1/2}} \quad (6)$$

Substituting (6) into (3) we find that

$$\Delta y = 2R\sin\theta_1\,(\cos\theta_1\,(N_2^2/N_1^2 - \sin^2\theta_1)^{-1/2} - 1)\,. \quad (7)$$

We simplify (7) by assuming $n_2 >> n_1$ (which is reasonable for nuclear striations) and substituting (5) into (7). We find then that

$$\Delta y = R\,\frac{\tan\theta_1}{\cos\theta_1}\,\frac{\omega^2_{pe2}}{\omega^2}\,. \quad (8)$$

Thus, (8) is an estimate of the deflection of an electromagnetic wave with frequency ω as it propagates through a nuclear striation of density n_2 with an initial angle θ_1 with respect to the normal of the striation.

In general, striations are believed to be 100's m - few km in radius transverse to the ambient geomagnetic field; they are 100's km - 1000's km in length parallel to the magnetic field. For densities in the range $n_e = 10^8 - 10^{12}$ cm^{-3} we note that $\omega_{pe} = 5.6 \times 10^8 - 5.6 \times 10^{10}$ rad/sec; also, we are interested in electromagnetic waves with frequencies between range $\omega = 1.3 \times 10^{11} - 1.9 \times 10^{15}$ (i.e., $\lambda \sim$ cm - microns). Thus, $\omega_{pe}^2/\omega^2 << 1$ and based upon (8) we find that $\Delta y << R$ for most values of θ_1.

However, as implied earlier, the nuclear ionosphere will not contain one striation, but in fact hundreds or possibly thousands. Thus, as an electro- magnetic wave propagates through a HANE environment it will undergo *many deflections;* the cumulative effect will be substantially greater than the single deflection estimate given by (8). We propagate an electromagnetic wave through a series of striations of the same density. The half width of each striation (R_i) is determined at random based upon the distribution shown in Fig. 2. This distribution is based upon experimental evidence from the Checkmate test (Chesnut, 1972). It is not known if this distribution can be generalized to other bursts; nevertheless, it represents a physically realizable situation and is a good starting point for a striation model. Thus, we calculate the total deflection of the wave Δy_T after it has passed through N_s striations, i.e.,

$$\Delta y_T = \sum_{1}^{N_s} \Delta y_i = \sum_{1}^{N_s} R_i \frac{\tan \theta_1}{\cos \theta_1} \frac{\omega_{pe2}^2}{\omega^2} \qquad (9)$$

Using (9) we can calculate Δy_T for several relevant frequency ranges under a variety of possible HANE conditions. Also, the total distance travelled by the wave is calculated as follows. We assume that there is a region of ambient plasma half width R_i following a striation of half width. The total distance X_T is then found to be

$$X_T = \sum_{1}^{N_s} 4R_i/\cos \theta_1 \quad . \qquad (10)$$

III. RESULTS

In Figs. 3-5 we plot the total beam deflection Δy_T (meters) versus electron density n_e (cm^{-3}) for several radiation wavelengths as the beam passes through 1000 striations. We vary n_e from the maximum ambient value ($n_e \approx 10^6$ cm^{-3}) to the maximum nuclear value ($n_e \approx 10^{12}$ cm^{-3}). In each figure we also show the variation of Δy_T with the incident angle θ_1; the angles considered are $\theta_1 = 15°$ (A), $\theta_1 = 30°$ (B), $\theta_1 = 45°$ (C), $\theta_1 = 60°$ (D), and $\theta_1 = 75°$ (E). We note that Δy_T can vary by two orders of magnitude as θ_1 varies from $\theta_1 = 15°$ to $\theta_1 = 75°$. Finally, the total distance the wave propagates is also indicated; the distances are $X_T \approx$ 3200 km (A), $X_T \approx$ 3700 km (B), $X_T \approx$ 4200 km (C), $X_T \approx$ 6500 km, and $X_T \approx$ 12000 km (E).

In Fig. 3 we show Δy_T (m) vs. n_e (cm^{-3}) for $\lambda = 10^{-6}$ m (1 μ radiation). The important result from this figure is that even under the most stressful condition (i.e., $n_e \sim 10^{12}$ cm^{-3} and $\theta_1 \sim 75°$) the maximum deflection experienced by the beam is < 1 cm; note that $\Delta y_T/X_T \lesssim 10^{-9}$. For lower values of electron density ($n_e \lesssim 10^9$ cm^{-3}) we find that $\Delta y_T \lesssim 10^{-5}$ m. Thus, it appears that 1μ radiation will effectively propagate in a straight line; even in a highly disturbed, multiburst nuclear environment.

In Fig. 4 we plot Δy_T (m) vs. n_e (cm^{-3}) for $\lambda = 10^{-5}$ cm (10 μ radiation). As expected, the deflection Δy_T is two orders of magnitude larger than the 1 μ case. We find that under the most stressing conditions that $\Delta y_T \sim 1$ m which may be significant depending on the purpose of the beam; note that $\Delta y_T/X_T \lesssim 10^{-7}$. On the other hand, for less severe conditions ($n_e \lesssim 10^9$ cm^{-3}) we see that $\Delta y_T \lesssim 1$ mm; this should not degrade an SDI system using 10 μ radiation.

Finally, in Fig. 5 we plot Δy_T (m) vs. n_e (cm^{-3}) for $\lambda = 10^{-2}$ m (1 cm radiation). We find that the deflection Δy_T can be substantial. For severe conditions ($n_e > 10^{10}$ cm^{-3}) the deflection is $\Delta y_T > 100$ m which can clearly impact SDI microwave systems in an adverse manner. Even under moderate situations, $n_e \lesssim 10^9$ cm^{-3} we find that $\Delta y_T \lesssim 10$ m which could be significant. Thus, microwave systems can be severely degraded in a HANE environment because of refraction effects.

IV. CONCLUSION

We have presented a preliminary analysis of electromagnetic wave refraction in a nuclear environment. We derive a relatively simple expression for the total deflection of a beam as it propagates through a number of nuclear striations [see (8)]. The nuclear striation model we consider assumes that the striations are aligned with the earth's magnetic field; the distribution of the striation width transverse to the magnetic field is based upon data from the Checkmate burst [see Fig. 2]. We present results for the deflection of 1μ, 10μ, and 1 cm radiation propagating through 1000 striations. The striation density n_e is varied from $n_e = 10^6$ cm^{-3} to $n_e = 10^{12}$ cm^{-3}, and the incident angle of the beam θ_1 is varied from $\theta_1 = 15°$ to $\theta_1 = 75°$. For the number of striations considered the beam travels a total distance $X_T = 3.2 \times 10^3 - 1.2 \times 10^4$ km, depending on the angle θ_1.

Our results indicate that 1μ and 10μ radiation will be able to propagate through a severely disturbed nuclear environment with little deflection ($\Delta y_T < 10$ cm). SDI systems using these types of radiation should not be adversely affected by refractive effects. On the other hand, 1 cm radiation can be severely impacted by the nuclear environment. Microwaves can undergo deflections much greater than 10 m for $n_e \gtrsim$

10^3 cm^{-3}. SDI systems using microwaves can then be expected to be severely degraded in a multi-burst nuclear environment.

We note that one technique to minimize adverse refractive effects is to propagate beams perpendicular (or very nearly perpendicular) to the geomagnetic field. In this situation $\theta_1 = 0$ and the geometrical factor in (8) becomes very small (i.e., $\tan\theta_1/\cos\theta_1 \sim \theta_1 << 1$), thereby reducing Δy_T. Whether or not this idea is operationally feasible, or even useful, for proposed SDI systems will have to be determined by SDI architects. Also, we note that this mitigation technique is only viable after the earth's magnetic field has returned to ambient conditions (several minutes after the final burst).

Finally, we re-emphasize that we have only considered refractive effects in a simplified geometry, and that other aspects of beam propagation (e.g., focussing, modulation, etc.) must be studied in order to determine the impact of a nuclear environment on proposed SDI systems. Also, we note that we only considered beam propagation in a plane containing the geomagnetic field. Another problem is beam propagation in the plane transverse to the magnetic field. In this plane the beam can also undergo a series of deflections as it propagates through a series of striations. However, rather than causing a net spatial deflection as in the situation considered in this paper, the beam will undergo a net angular deflection (Brecht, 1988). It should be noted that this effect is sensitive to the actual shape of the striations in the plane transverse to $\underset{\sim}{B}$ (e.g., circular, elliptical, etc), a subject of current interest to the HANE community.

ACKNOWLEDGMENTS

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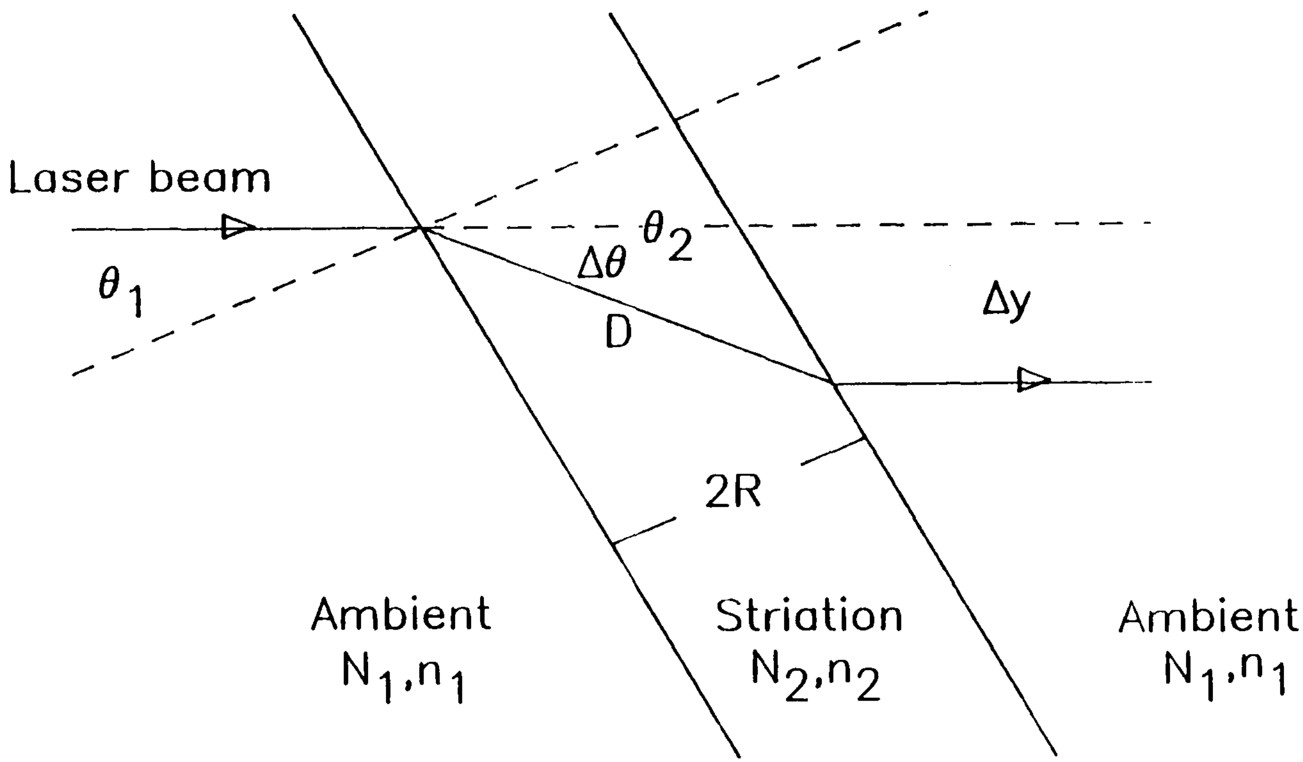

Fig. 1) Geometry of an electromagnetic wave propagating through a single striation.

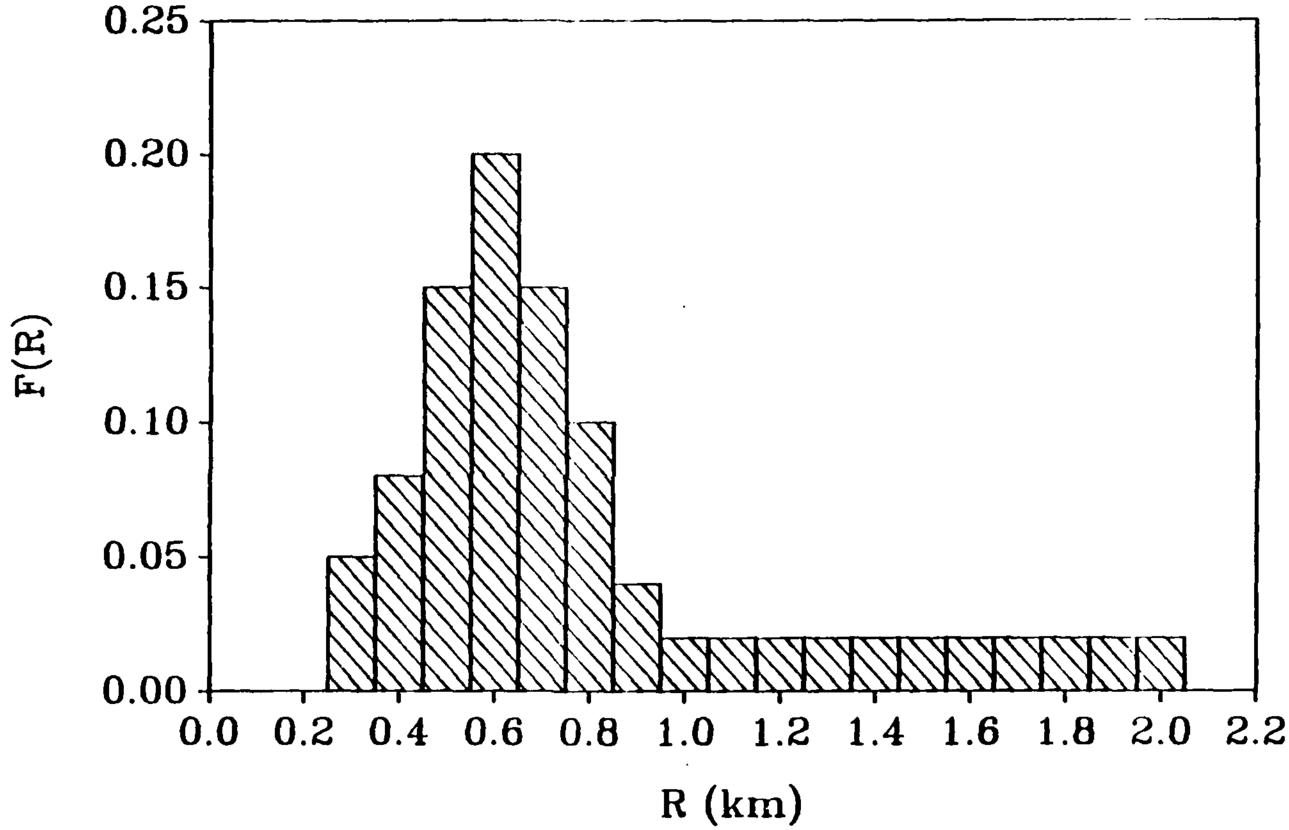

Fig. 2) Distribution function F(R) of striation half-widths transverse to the geomagnetic field (in kms).

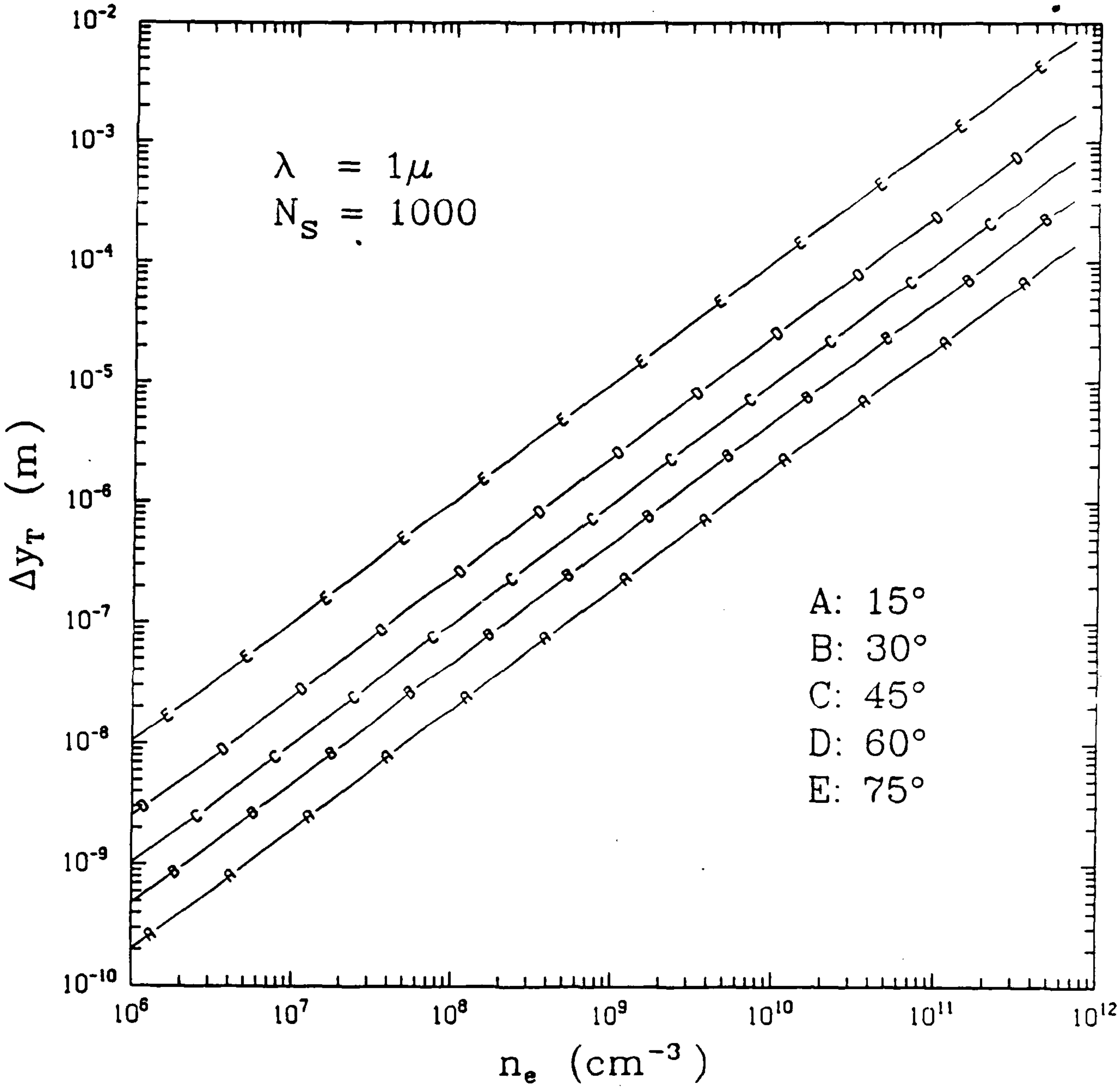

Fig. 3) Plot of Δy_T vs. n_e for $\lambda = 10^{-6}$ m, $N_s = 1000$, and $\theta_1 = 15°$ (A), 30° (B), 45° (C), 60° (D), 75° (E).

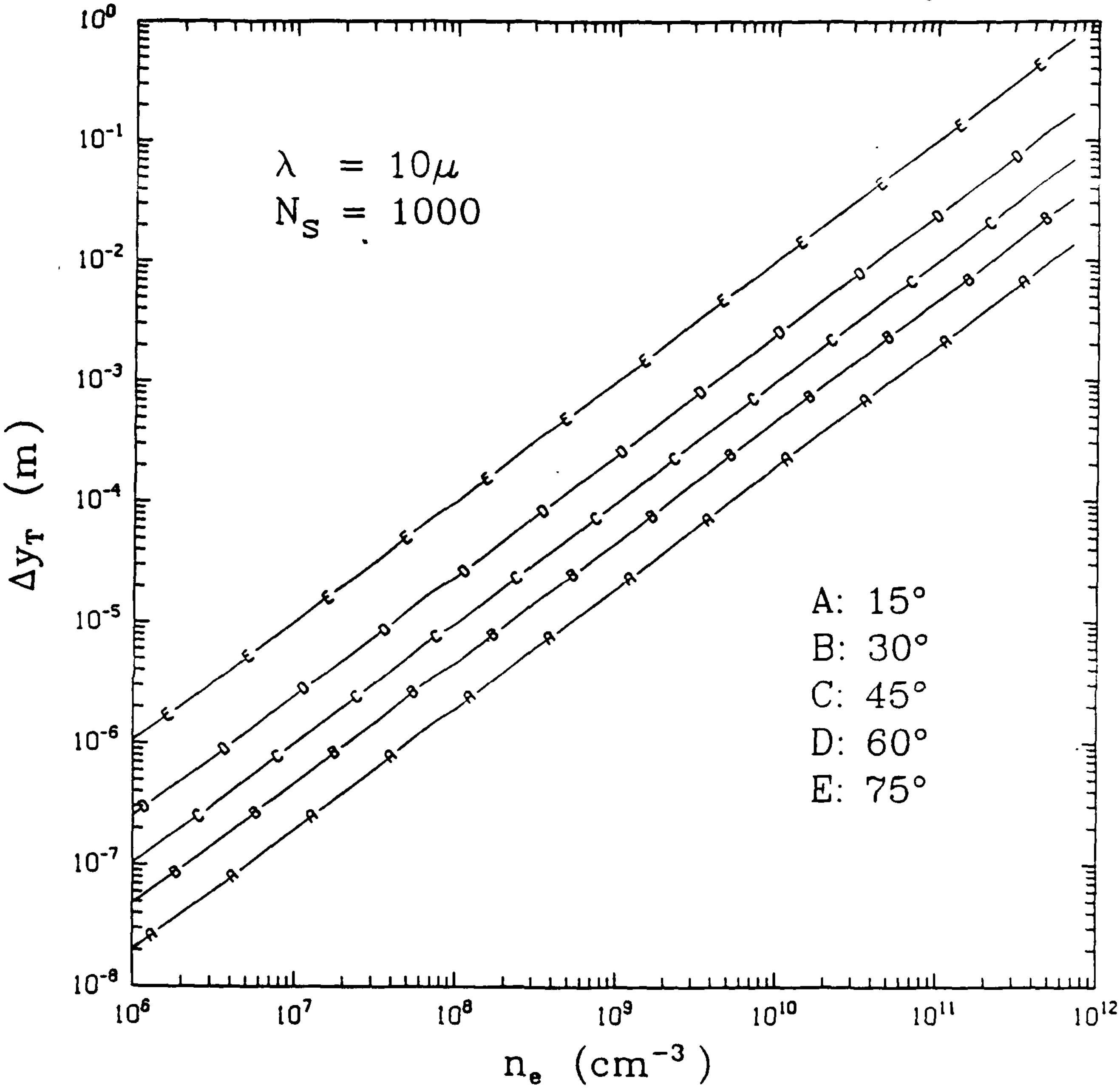

Fig. 4) Plot of Δy_T vs. n_e for $\lambda = 10^{-5}$ m, N_s = 1000, and θ_1 - 15° (A), 30° (B), 45° (C), 60° (D), 75° (E).

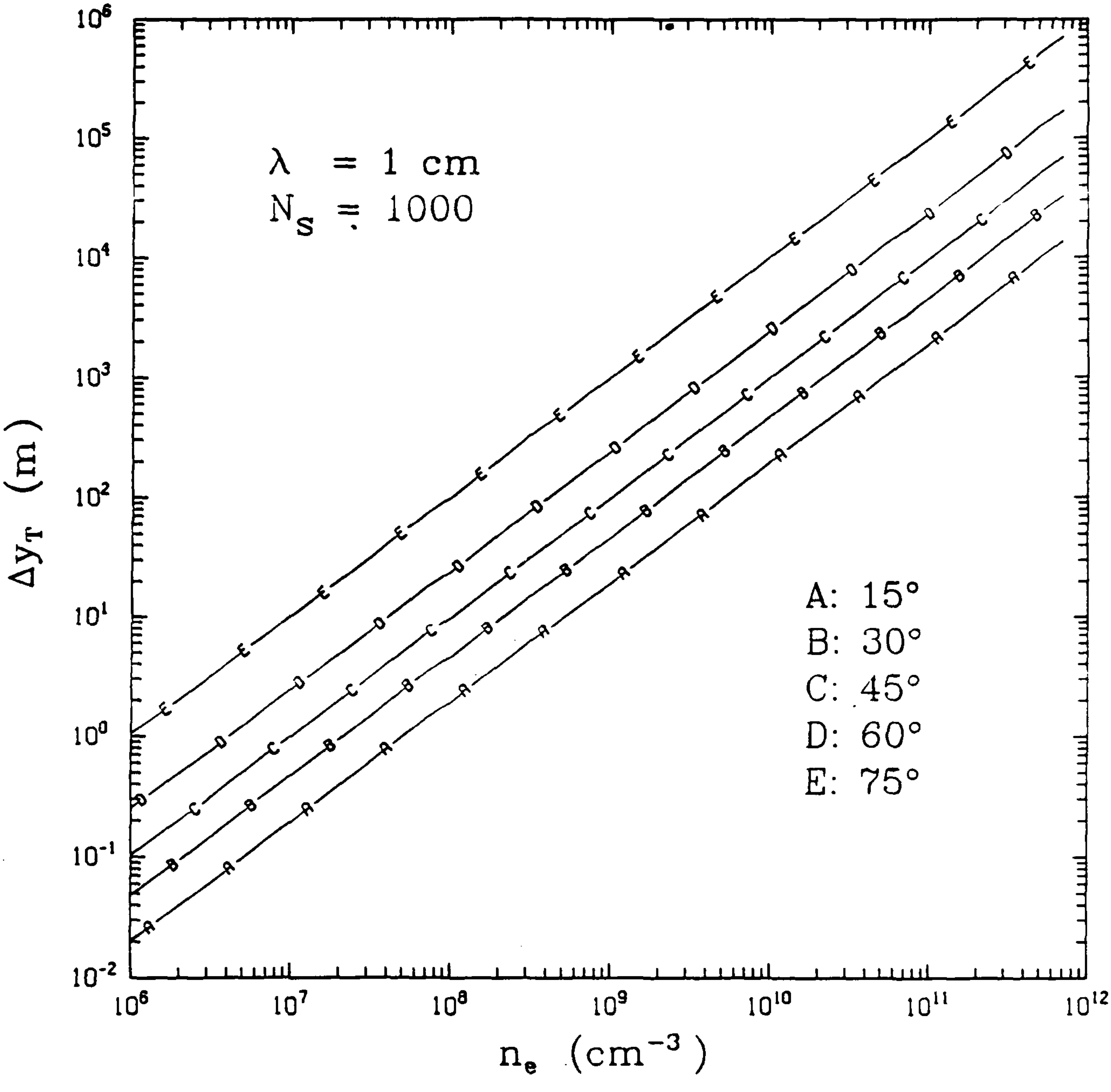

Fig. 5) Plot of Δy_T vs. n_e for $\lambda = 10^{-2}$ m, $N_s = 1000$, and $\theta_1 = 15°$ (A), 30° (B), 45° (C), 60° (D), 75° (E).

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